RILLES, RIDGES, AND DOMES - CLUES TO MARIA HISTORY

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SUMMARY

The lunar rilles, maria ridges, and maria domes are spacially associated with low areas of the lunar surface, the maria, and immediately adjacent terrae. The spacial association implies a genetic relationship. The morphology and structural setting of most of the rilles suggests that they are tectonic features of tensional origin produced by downward bending of maria borders during a stage of maria foundering. The domes and ridges were most likely produced by small central eruptions or by laccolithic intrusions. Most of the ridges appear to be volcanic structures which grew above dike feeders during the last stages of maria filling. Age relationships and structural settings of the rilles and ridges further suggest that the formation of these features took place in sequence, ridges and domes followed by rilles. It is suggested here that this sequence of events occurred repeatedly during a long history of maria growth and that the maria grew to their present sizes by successive stages of volcanic inundation and collapse. Circular maria probably resulted from a simple enlargement of initially circular depressions whereas the irregularly shaped maria resulted from a coalescence of two or more growing basins or depressions.

INTRODUCTION

Modern interpretations of the mechanism of formation of the maria are varied. Kuiper (1954) has postulated that the maria are composed of lava flows originating in the Moon's interior by radio-active heating and released to the surface by fracturing produced by impacts of great planetesimals. Urey (1962) agrees that the maria are composed of lava but states that the lava may have been produced by liquefaction of impacting low velocity planetesimals. Gold (1955), on the other hand, has stated that the dark areas of the Moon are not lava but thick layers of dust formed by various processes of erosion in the highlands and transported to the low areas where they were deposited. Baldwin (1963) agrees with Kuiper and Urey that the maria are made up of lava flows, but disagrees in the postulated mechanism of formation or time of eruption. He maintains that they originated in the interior of the Moon through radioactive heating and were erupted to the surface long after the maria basins had been formed by impact of large bodies. More recently Lowman (1963) has concluded that the maria are the lunar equivalents of terrestrial lopoliths, large basins filled mainly with basaltic rocks overlain by tuffs, rhyolites, and granophyres.

The purpose of this paper is to examine the morphology and structural setting of those topographical features which are associated spacially with the maria in an attempt to throw more light on the possible mechanism of origin of those regions of the Moon. Rilles, ridges, and domes are uniquely associated with the maria and the immediately adjacent terrae. For this reason it seems certain that they were produced by the same processes which gave rise to the maria. A knowledge of their form and structure, therefore, should provide the most reliable basis for interpreting the mechanism of maria formation.

THE RILLES

Lunar rilles are trenches in the lunar surface. Some are straight over large distances, some are arcuate in plan, some exhibit irregularly branching patterns, and others are exceedingly sinuous. Because of their morphological diversity it is convenient to describe each group individually.

The Straight Rilles

The most obvious rilles on the lunar surface are straight in trend. They range in length from barely detectable to hundreds of kilometers. Each is long relative to its width, the maximum width observed being approximately 5 km. The straight rilles rarely occur singly but rather are found in sets, often exhibiting en echelon patterns. Some of the most conspicuous straight rilles of the lunar surface are the Cauchy set (1 in Fig. 1), the Apollonius set (2 in Fig. 1), the Goclenius set (3 in Fig. 1), the Mersenius set (4 in Fig. 1), and the Ariadaeus-Hyginus system (5 in Fig. 1). All these rilles are associated with maria borders. The Cauchy set borders Mare Tranquillitatis on the northeast; the Apollonius set is found on the northeast margin of Mare Fecunditatis; the Goclenius set bounds Mare Fecunditatis on the southwest; the Mersenius set lies near Mare Humorum to the northeast; and the Ariadaeus-Hyginus system is located immediately to the southeast of Mare Vaporum. Some of these rilles occur entirely within maria materials, some entirely within the terrae, and others occur in both.

The general form of the rilles is that of a long narrow trench with inward dipping walls. In detail, a single rille is often seen to consist of a series of en echelon trenches, the pattern duplicating in miniature that observed on a large scale for various members of the rille set. Cauchy I Rille and rilles of the Ariadaeus-Hyginus system in particular show en echelon patterns. Many straight rilles are characterized by the presence of crater chains along their floors and by the presence of an abundance of small craters in bordering regions. Small crater chains are present along Cauchy I Rille and along members of the Apollonius and Goclenius sets and are particularly abundant along members of the Ariadaeus-Hyginus system. In addition, small crater chains occasionally cross the structural trends of many of the rilles, particularly in areas where the main structural grain is crossed by a less conspicuous set of rilles. Grid patterns so defined are visible at the southeast end of the Cauchy set in the terrae septum which divides Mare Tranquillitatis from Mare Fecunditatis, in the terra between Mare Fecunditatis and Mare Crisium and in the terra near the Godenius set. In all cases, both sets of rilles of the grid systems parallel old, subdued structural grains in the terrae. The parallelism of old and young features in both sets of the grid systems is indicative of resurgent movements on old structural lines created during an earlier phase of lunar history. The relative ages of the younger rilles is apparently the same.

The Ariadaeus-Hyginus Rille system exhibits many of the features characteristic of the straight rilles and for that reason it is treated in some detail.

The Ariadaeus-Hyginus Rille system is one of the most prominent markings on the lunar surface. The system is located immediately to the southeast of Mare Vaporum. It consists of two sets, the northwesterly trending Hyginus set and the west-northwesterly trending Ariadaeus set. The Hyginus set is represented by a single rille, Hyginus, which extends some 100 km northwestward from the crater Hyginus. The rille cuts mare material throughout most of its extent but passes into island mountains of terra material where it bifurcates and dies out. The rille is a broad, shallow depression characterized by the presence of a continuous crater chain extending northwestward from the crater Hyginus for half its length. The trend of the rille is the same as the linear grain of the terra of this region, the radial Imbrium pattern.

The Ariadaeus set consists of two prominent rilles, Ariadaeus and a parallel structure normally considered to be part of the Hyginus rille. The rille set extends from the terra immediately south of Mare Vaporum southeastward through the crater Hyginus and across the terra to Mare Tranquillitatis. The southeastern portion of the rille set can be seen in Fig. 2. The two major rilles of the set are en echelon in plan, one becoming prominent where the other dies out. The rille passing beneath the crater Hyginus extends about 115 km to the east-southeast before it dies out in the terra north of the crater Agrippa. It also extends westward from the crater Hyginus for 75 km as a series of

4 en echelon segments eventually terminating against the terra. East of Hyginus the rille is a prominent depression consisting of a series of troughs rather than a single valley. The troughs appear to be offset at two places, but there is no indication that the offsets were produced by lateral displacements. The sense of the offsets is identical to the en echelon pattern exhibited throughout the rille set. Crater chains trend across the strike of the rille precisely in those places where the apparent offsets occur. Occasional craters with diameters greater than 1 km occur within the depression and small craters are more numerous near the rilles than elsewhere on the lunar surface. The rille immediately east of Hyginus is 3 to 4 km wide, shallow, and has inward dipping walls.

The Ariadaeus Rille becomes prominent where the more southerly rille dies out. It extends across the terra some 270 km to the edge of Mare Tranquillitatis. The rille has been described in excellent detail by Fielder (1961). It is about 5 km wide in its middle region, shallower than wide, and has several apparent offsets along its course. The apparent offsets are in the same sense already mentioned and are more likely a result of en echelon development of the trench rather than displacement by wrench faulting. There are fewer craters along this rille than along the other members of the set, yet one prominent chain of four craters can be seen along the foot of the northern wall of the rille midway between the craters Silberschlag and Ariadaeus. The rille terminates at Mare Tranquillitatis in a cluster of craters. Branches from the rille extend southeastward into Mare Tranquillitatis and form a family of structures bordering the mare on the southwest.

The Arcuate Rilles

There are numerous examples of arcuate rilles on the lunar surface, particularly around Mare Serenitatis, Mare Imbrium, and Mare Humorum. The arcuate rilles all have their concave sides toward the mare about which they are located. The best developed arcuate structures are those marginal to Mare Humorum. These are considered as representative of the group.

The most spectacular arcuate rilles on the lunar surface are found on the east and southeast margin of Mare Humorum. There the Hippalus and Campanus Rilles (6 in Fig. 1) form a set of great arcuate structures extending over hundreds of kilometers of the Moon's surface. The rilles occur in the terra but cut mare material where embayments extend into the terra. These rilles are similar to the straight rilles in all respects except for their shape in plan. They are long, narrow, shallow troughs with inward dipping walls and low relief floors. The arcuate rilles may join as do Campanus I and Hippalus II, or they may occasionally be connected by short transverse structures.

Leibig I Rille is located on the western margin of Mare Humorum (7 in Fig. 1 and Fig. 3). It extends from just north of the crater Leibig G around the margin of Mare Humorum to the Crater Gassendi. Immediately north of the crater Leibig G it has monoclinal or normal fault morphology with the mare side down over a distance of 70 km. Directly on trend this structure assumes normal rille morphology for 70 or 80 km. Then, for about 25 km there is no indication of any structural modification of the surface, but directly on trend a structural line reappears with normal fault morphology, again with the mare side down. This structure extends into the old crater Gassendi where it dies out.

Origin of Straight and Arcuate Rilles

The straight and arcuate rilles are similar in morphology to terrestrial fault structures. Most have graben morphology, long fault troughs bounded by inward dipping normal faults, shallower than wide, frequently displaying en echelon development. Some notable examples of very large terrestrial grabens are the Rhine Valley and the East African Rift Valleys. There are innumerable terrestrial grabens which are of a scale comparable to the lunar rilles, although many of these no longer exist as surface depressions. The greater mobility of the Earth's crust coupled with the processes of erosion and deposition have destroyed many of these as landscape features, yet the record remains in the rocks. Terrestrial grabens are characteristically accompanied in space and time by volcanism, both along the trench and bordering it. In addition there are examples of normal fault morphology on the lunar surface. The Straight Wall bordering Mare Nubium on the west and portions of the Leibig I Rille are excellent examples. There is little doubt that these structures have formed by relative downward movements of the maria.

Normal faults and normal fault bounded troughs (grabens) develop on the Earth where the crust is under tension. They are formed by the only mechanism of extension of which a brittle crust is capable. Extension of the crust is rarely seen as a simple pulling apart of crustal segments, but rather it is accomplished by bending of the brittle crust in response to vertical movements, either positive upward movements or by differential downward movements. During the bending the brittle crust over the bend is under tension and it fractures. The fractures by which extension is accomplished reach deeply into the Earth, deeply enough to tap actual or potential magmas, for volcanic activity is spacially related to normal faulting. The great morphological similarity between lunar rilles and terrestrial grabens has been pointed out. The structural setting of the rilles is one where regional tension is to be expected. All the rilles discussed are in regions bordering the low lying maria. The structural setting of all the major rilles is shown in Fig. 1. The relationship between the rilles and the maria borders is striking. It is well known that the maria are low areas of the lunar surface. Thus the rilles are located precisely in those locations where tension is to be expected, where the lunar surface bends down from the higher terrae to the lower maria. There is thus little doubt that the lunar rilles are structural features of tensional origin. They are almost certainly grabens and normal faults.

The Irregularly Branching Rilles

There are many examples of complicated rille patterns on the lunar surface, patterns characterized by frequent branching and spoke-like extensions from a point. This pattern is most frequently seen in old, large craters such as Gassendi, Mersenius, Helvetius and Posidonius, but it is also prominently displayed in the region near the crater Triesnecker. The rilles within Gassendi and near Triesnecker are typical.

The crater Gassendi lies on the northwestern border of Mare Humorum (8 in Fig. 1 and Fig. 3). It is a large crater with a 110 km diameter and a depth of 2000 meters. There is a central cluster of three peaks with elevations approximately that of the rim. The crater floor has the same elevation as the nonmountainous terra to the west and is slightly higher than Mare Humorum to the south. The crater is old by relative standards, having the large crater Gassendi B superimposed on its northern rim and a number of smaller craters on its floor. Furthermore, the southern crater wall has been breached by Mare Humorum material and a small portion of its floor has been inundated. The arcuate rille Leibig I which borders Mare Humorum on the west cuts the southwest wall of the crater. Gassendi is thus at least older than the last phase of filling of Mare Humorum. A number of intersecting rilles lie within the walls of Gassendi. The pattern has no orientation relationship with the mare border rilles, but instead is strikingly similar to a common fracture pattern in brittle rocks above domical uplifts on the Earth. The striking similarity of form suggests a somewhat similar mechanism of origin. The faults in the Gassendi structure suggest that the central region of the crater has been upwarped and that the faulting is a result of elastic deformation in the upper brittle layers of the lunar surface above a plastic or visco-elastic region of deformation. It is possible that the driving force was gravitational, i.e., the crater after formation was out of gravitational equilibrium and subsequent isostatic adjustment occurred with upwarping of the central crater region. Whatever the mechanism, the doming and fracturing must have been complete before the last stages of mare filling because the rilles terminate against the mare material in the southwestern part of the crater.

The same kind of pattern just described occurs in the region between the craters Hyginus and Triesnecker. It is present over a much larger area, however, and is marked by frequent crater chains within the rilles and by small crater clusters in surrounding regions. The pattern can best be explained by normal faulting in a region of crustal tension. The structural setting of the region is such that crustal bending, and hence crustal tension, is to be expected. The Triesnecker area is bordered on three sides by low regions of the lunar crust, Sinus Medii to the southwest, Mare Vaporum to the north, and a very low lying region of terra material to the east and southeast. An arch in the Triesnecker area could have developed by differential downward movements, greater in the low regions than in the fractured portion. Arching of brittle rocks could produce exactly the kind of fracture pattern observed.

The Sinuous Rilles

A number of irregular rilles, snaking in plan, can be seen on the lunar surface. These rilles are usually smaller and less obvious than the straight and arcuate structures described above. Some examples of the sinuous rilles are Schröters Valley, Hadley Rille, The Aristarchus Rilles III through VIII, the Prinz and Harbinger Mountains Rilles, La Hire I Rille, and Marius Rille.

The La Hire I (9 in Fig. 1) and Marius rilles are characteristic of those occurring on the low relief maria. They are narrow and sinuous in over-all plan, but often have reaches which are straight for several kilometers. Occasional crater chains are present along portions of the rilles. Neither is structurally associated with maria ridges although some sinuous rilles do follow along the crests of the ridges. These appear as more or less continuous crater chains. The exact mode of origin of the sinuous rilles not associated with maria ridges is uncertainly known. Most probably have been the locus of minor volcanic activity and as such are probably narrow trenches of tensional origin.

The sinuous rilles of the Harbinger Mountains and the Aristarchus region are peculiar in that they most commonly have an associated crater or crater chain at their heads. The shape of the rilles is similar to that of a terrestrial stream channel. The trend of the rilles is generally downslope from the terminal crater. W. S. Cameron (1964) has described the unique character of these rilles and their similarity to eroded terrestrial valleys. She has proposed a mechanism of formation by eroding glowing avalanche eruptions. Glowing avalanche eruptions on the Earth are known to be erosive but the magnitude of the rilles is such as to require very extensive erosion. The sinuous valleys may have been eroded by glowing avalanche eruptions, but the writer believes that they owe much of their development to fractures which developed in the rigid crust during a process of arching. Most of the sinuous rilles in question lie within a rectangular mountainous block. The relief of the block suggests that it is made up of premaria material. The area therefore may represent an arch of older rocks surrounded on all sides by lower lying mare material of Oceanus Procellarum. Fracturing of the arched region may have produced the rilles and at the same time provided avenues of ascent for volcanic materials, the eruption of which further modified the rilles.

THE RIDGES

Maria ridges (wrinkle ridges) are irregularly trending low ridges which are found exclusively on the maria. They are at most a few hundred meters high and are broad, up to 20 km in width at the base. They are usually sinuous in plan but a few are straight. Some are circular. Those which occur in the circular maria are usually arcuate in over-all plan with their concave sides toward the maria centers. The ridges are often discontinuous, frequently en echelon in pattern and in many cases have multiple crests. A prominent ridge on the eastern portion of Mare Serenitatis is shown in Fig. 5. Noncircular ridge crests are occasionally marked by crater chains and narrow sinuous rilles. The ridges in the circular maria mostly occur in the border zones but always interiorly with respect to the border rilles. This relationship can be seen in Fig. 1. The ridges and rilles rarely cross; in those cases where they do the rilles are the younger (see Fig. 5). Ridges in other maria and in Oceanus Procellarum do not have a simple arcuate plan. Many occur in linear belts as in Oceanus Procellarum and Mare Frigoris.

The formation of the maria ridges is closely linked with maria formation. Their presence on the maria surfaces indicates a post- or late-maria age. They are definitely older than post-maria craters, and probably older than most rilles. The mechanism of origin of the ridges is not the same for all. Some are undoubtedly buried or partially buried ridges. This origin is most obvious in the case of ghost craters where ridges on the maria surfaces define circular structures.

Differential compaction of sediments over bedrock highs to produce ridge structures is a well-known terrestrial feature. Similar structures could have developed on the Moon by differential compaction of maria materials over old crater rims. If maria development took place over a lengthy period of time numerous ring structures would have been produced on their surfaces at various stages of maria filling. Those developed just prior to the latest filling would be reflected in the surface topography. All gradations between barely recognizable ring structures and well-defined craters can be observed. This indicates that craters developed at various stages of maria growth and are in different stages of inundation, some partially covered on their flanks, some breached and partially filled, and some completely covered - their presence now recorded by low relief ridges where differential compaction over their rims has given them surface expression.

A few linear ridges in the maria near the terrae may have been produced in the same manner. Occasional ridges in the terrae can be traced into maria regions as maria ridges. Possible examples can be seen at the north edge of Mare Fecunditatis and at the south edge of Mare Crisium. Such relationships are not numerous, however, and this mechanism cannot account for the origin of most maria ridges.

Baldwin (1963) stated that maria ridges are of compressional origin produced by the collapse of great lava domes which are now the maria. This process could produce tension on maria borders and simultaneous compression in their interiors. The over-all distribution of maria ridges, however, does not support this hypothesis. The ridges in the circular maria occur in peripheral regions and not in the interior. It is not likely that collapse of great volcanic domes would produce marginal compression only.

Maria ridges are superficially similar to pressure ridges produced in the frozen surface crust of still flowing lava sheets. Pressure ridges develop on terrestrial basalt flows with their long axes parallel to flow fronts. If the maria are composed of vast flows of lava with relatively low viscosity, maria ridges could have been produced by this mechanism. It is highly unlikely, however, that such flows could have been so extensive as to have individual flow fronts hundreds of kilometers long. It is improbable, therefore, that the ridges are flow features.

The only other possible mode of formation of maria ridges is that they are volcanic ridges built over feeder dikes during fissure eruptions. Strict terrestrial analogies are rare because of the rapid rates of erosion on the Earth. The best known examples of surface ridges produced by fissure eruptions are in Iceland. A number of eruptions have taken place there during historic times, spreading highly fluid basalt and fine ejecta over wide areas. The flows and ejecta originated from innumerable points along a fissure, obviously fed by dikes or dike swarms.

It is worthwhile to summarize the typical sequence of events in an Icelandic eruption cycle. Eruption begins with fissure opening accompanied by explosive activity producing local accumulations of breccia. Following the initial explosive stage enormous volumes of highly fluid magma pour out flooding wide areas. During this stage intense fountain activity occurs along the fissure. As the magma emission phase wains, mildly explosive activity continues along the fissure building small breccia ramparts and spatter cones. The ramparts and cones coalesce to form discontinuous linear ridges over the feeder dikes. The ridges so formed are characterized by numerous small adjacent craters along their summits. Further modification of the ridges sometimes occurs by renewed rise of liquid magma producing small lava lakes and short flows. At the end of the eruptive cycle magma withdrawal takes place in the feeder dikes leaving partially open fissures bridged by congealed surface lavas. Local collapse of the lava cover produces debris filled trenches along the ridges.

It is suggested here that most of the maria ridges had a similar mode of origin. The mechanisms of eruption probably differ in detail because of the differences in the physical environments on the Earth and on the Moon. The similarities are that vast volcanic outpourings were fed from fissures of tensional origin and that in the last stages of any one eruptive cycle ridges were constructed above the fissures. The flows may have been produced either by highly mobile lavas similar to those of the Icelandic eruptions or by glowing avalanches which overflowed from the fissures and formed widespread ignimbrite sheets.

The location of many of the ridges in the border regions of each of the circular maria suggests that many of the feeder dikes were intruded in arcuate tension fractures produced during a stage of downwarping of the circum-maria crust. Some linear ridges are present in the circular maria as well. Their trends often coincide with prominent linear trends in nearby terrae as Arthur (1962) has pointed out. Old fractures in the bedrock certainly have exerted control on the final patterns developed by dike intrusions.

THE DOMES

Maria domes are broad, low features with basal diameters of a few kilometers and heights of a few hundred meters. Many have summit craters and a few have summit spines. The distribution of maria domes is shown in Fig. 1. Arthur (1962) has shown that the domes are restricted to the maria (but do not occur in all of them) that the domes are further restricted to maria borders or areas where evidence indicates a shallow fill, and that the domes occur in groups.

The morphology of the domes is such that a volcanic origin is highly probable. The structures could result from laccolithic intrusions in stratified maria materials or from extrusion of magma in the form of endogenous domes or small shield volcanoes. Laccoliths form when the hydrostatic pressure of an intruding magma is sufficient to lift the weight of overlying stratified rocks. The intruding magma then spreads laterally along bedding planes and lifts the overlying rocks to produce a lens shaped mass of intrusive rock covered by a dome of stratified rocks. Rocks over the arch are frequently fractured and eruptive laccoliths result.

Endogenous domes are lava domes which grow from within. They result when highly viscous lava reaches the surface. The upper surface of the lava solidifies and becomes fissured, both by cooling contraction and by continued expansion of the dome by addition of molten material from below. Such domes grow intermittently often accompanied by explosive activity and occasional lava flows. The bulk of the growth is internal, however, producing small, steep sided domes. The final stage of dome formation is often marked by retreat of the lava in the conduit resulting in the formation of a subsidence crater in the apical region. Occasional spines are observed on dome summits where highly viscous lava has been extruded through summit fractures. The shapes of typical terrestrial endogenous domes are unlike those of the maria domes in that they are steeper and higher. The Puy de Sarcoui in Auvergne is a typical example; it has a height of 150 meters and a basal diameter of only 400 meters.

Relatively unmodified small shield volcanoes are known in Iceland. These domes are built of highly fluid lava streams which overflowed summit craters. The Icelandic domes rarely exceed 1000 meters in height and often measure less than 100 meters. Their basal diameters are great, as much as 20 times their height. The summit craters vary between 100 and 2000 meters in diameter. The form of these small shield volcanoes is thus quite comparable with that of the maria domes. The domes, then, are most likely laccoliths or small shield volcanoes. Precise age relationships are uncertain but they must have been produced during the most recent phase of maria volcanic activity.

INTERPRETED MARIA HISTORY

The morphology and structural setting of most of the lunar rilles indicates that they are tectonic features of tensional origin produced in the lunar surface rocks by late downward bending movements along the borders of the maria. The maria ridges and domes are also found in maria border regions. Their morphology points toward a volcanic origin. Most of the ridges are probably volcanic ridges constructed above dike feeders intruding along tension fractures. The domes appear to be produced by either small central volcanic eruptions or laccolithic intrusions of volcanic rocks. The ridges and domes also occur in border regions of the maria where crustal tension allowed large scale intrusion of feeder dikes. The maria ridges are located on the mare side of the rilles and are rarely in close proximity to the latter structures. Rare age relationships further indicate that the ridges predate the rilles. This suggests that the formation of the domes, ridges, and rilles was part of an orderly sequence of events that probably occurred repeatedly during a long history of maria growth. Accordingly, the natural history of the maria may be reconstructed.

The maria at some time in the past existed as low areas on the lunar surface. The circular outlines of many of the maria have been taken by many as evidence of an impact origin. Other origins are possible. Whatever their origin the basins were filled by a process which took a finite and probably lengthy period of time. Evidence as to the order of magnitude of that time interval is lacking. Baldwin (1963) has presented extensive evidence that the maria basins remained unfilled for a long time interval. His reasoning is based on the assumption that the maria basins were formed by hypervelocity impact. Identical reasoning does not apply if the basins are assumed to have formed by some other mechanism; but whatever mechanism of formation is envisaged a lengthy period of time is required to account for the details of maria formation.

Volcanism began some time after basin formation. The basin filling is certainly not exclusively fragmental material or dust. Debris probably does form a surficial covering but an excessively deep layer, unless very effectively bonded, would not behave elastically to produce the rille structures,[1] nor could volcanic crater chains in the rift valleys or the snaking maria ridges be accounted for. The filling is almost certainly volcanic. Evidence as to the composition of the lavas, however, is not available. The maria basins are probably not of the same age. They are certainly of different ages if they are of impact origin. It is reasonable to assume, however, that maria volcanic activity represents a particular period of lunar history when near surface temperatures had risen sufficiently to produce partial fusion of lunar material. The period of appropriate temperature distribution may have existed over a considerable time when catastrophic impacts or extensive crustal fracturing occurred. The basins then became the locus of extensive volcanic activity. Whether originating from catastrophic impacts or other energy sources, fracturing of the lunar surface to deep levels provided channels for actual or potential magma to ascend. It is suggested that the initial maria basins were flooded by volcanic material issuing from the fractures. Following the initial phase of lava flooding and outgasing the maria basins began to founder over the region of extensive magma removal. During the foundering regions peripheral to the basins were warped down producing tension fractures and faults, arcuate in some, linear in others. Further dike intrusions occurred along the newly opened fractures and

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[1]This interpretation is not contradicted by Ranger VII photographs.

and basin filling continued. The above sequence of events occurred repeatedly until the near surface temperatures were so modified by magma ascent that the process came to a virtual end with a phase of foundering to produce the presently observed rilles in the maria border regions. Slight volcanic activity continued with mild degassing producing explosion craters along many of the grabens on the maria borders. The last stage of extensive maria volcanism is recorded by the maria volcanic ridges which developed over the feeder dikes and by the maria domes. The proposed mechanism is illustrated graphically in Fig. 6.

According to this hypothesis the circular maria started as circular depressions. The irregularly shaped maria and Oceanus Procellarum represent a coalescence of growing basins which have flooded downwarped border areas. Mare Frigoris must have grown from an originally linear depression or series of linear depressions.

REFERENCES

ARTHUR, D. W. G. (1962). Some systematic visual lunar observations. In "The Moon" (Z. Kopal and Z. K. Mikhailow, eds.), pp. 317-324. Academic Press, New York.

BALDWIN, R. B. (1963). "The Measure of the Moon." Univ. of Chicago Press, Chicago, Illinois.

CAMERON, W. S. (1964). An interpretation of Schröter's Valley and other lunar sinuous rills. J. Geophys. Res. 69, 2423-2430.

FIELDER, GILBERT (1961). "Structure of the Moon's Surface." Pergamon Press, New York.

GOLD, THOMAS (1955). The lunar surface. Monthly Notices Roy. Astron. Soc. 115, 585-603.

KUIPER, G. P. (1954). On the origin of lunar surface features. Proc. Nat'l. Acad. Sci. 40, 1096.

LOWMAN, P. D., JR. (1963). The relation of tektites to lunar igneous activity. Icarus 2, 35-48.

UREY, HAROLD C. (1962). Origin and history of the moon. In "Physics and astronomy of the moon" (Z. Kopal, ed.). Academic Press, New York.

FIGURE TITLES

Fig. 1. The Moon showing the prominent rilles, ridges, and domes. Numbers indicate features considered at length in the text.

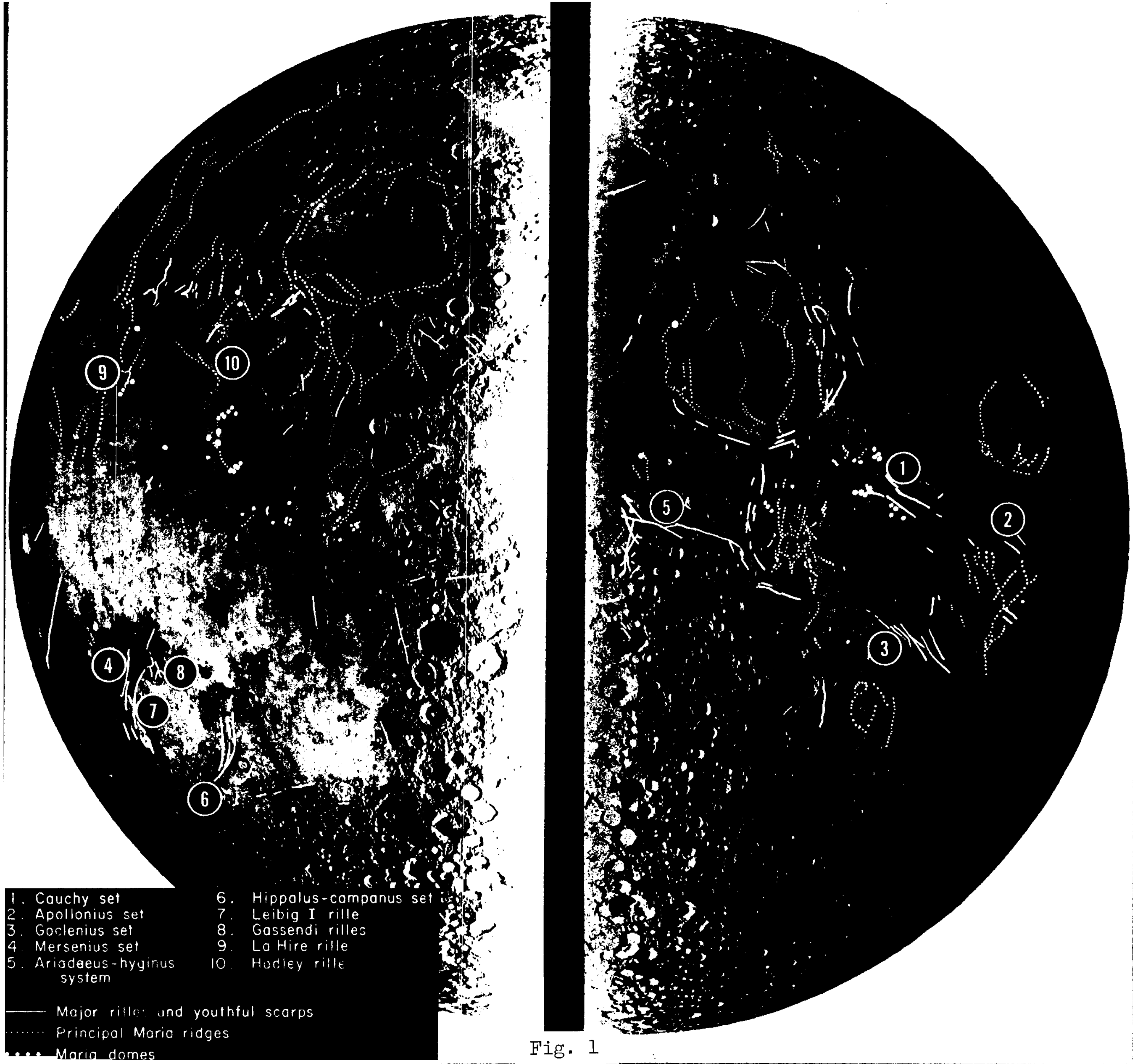
Fig. 2. Southeastern portion of the Ariadaeus Rille. Note the en echelon pattern of the rille segments. Also note the arcuate rille sets bordering Mare Tranquillitatis on the west and southwest and the more internally located ridges.

Fig. 3. Northern and western part of Mare Humorum showing the straight Mersenius Rille set, the arcuate Leibig I Rille at the immediate mare border, and the irregular rille pattern in the old crater Gassendi.

Fig. 4. The sinuous Hadley Rille. Note that the rille is composed of three segments terminating in craters.

Fig. 5. Typical maria ridges in the eastern part of Mare Serenitatis. Note the rilles in the south which cut the ridges.

Fig. 6. An idealized sketch of maria growth.



1. Cauchy set
2. Apollonius set
3. Goclenius set
4. Mersenius set
5. Ariadaeus-hyginus system
6. Hippalus-campanus set
7. Leibig I rille
8. Gassendi rilles
9. La Hire rille
10. Hadley rille
Major rilles and youthful scarps
Principal Maria ridges
Maria domes

Fig. 1

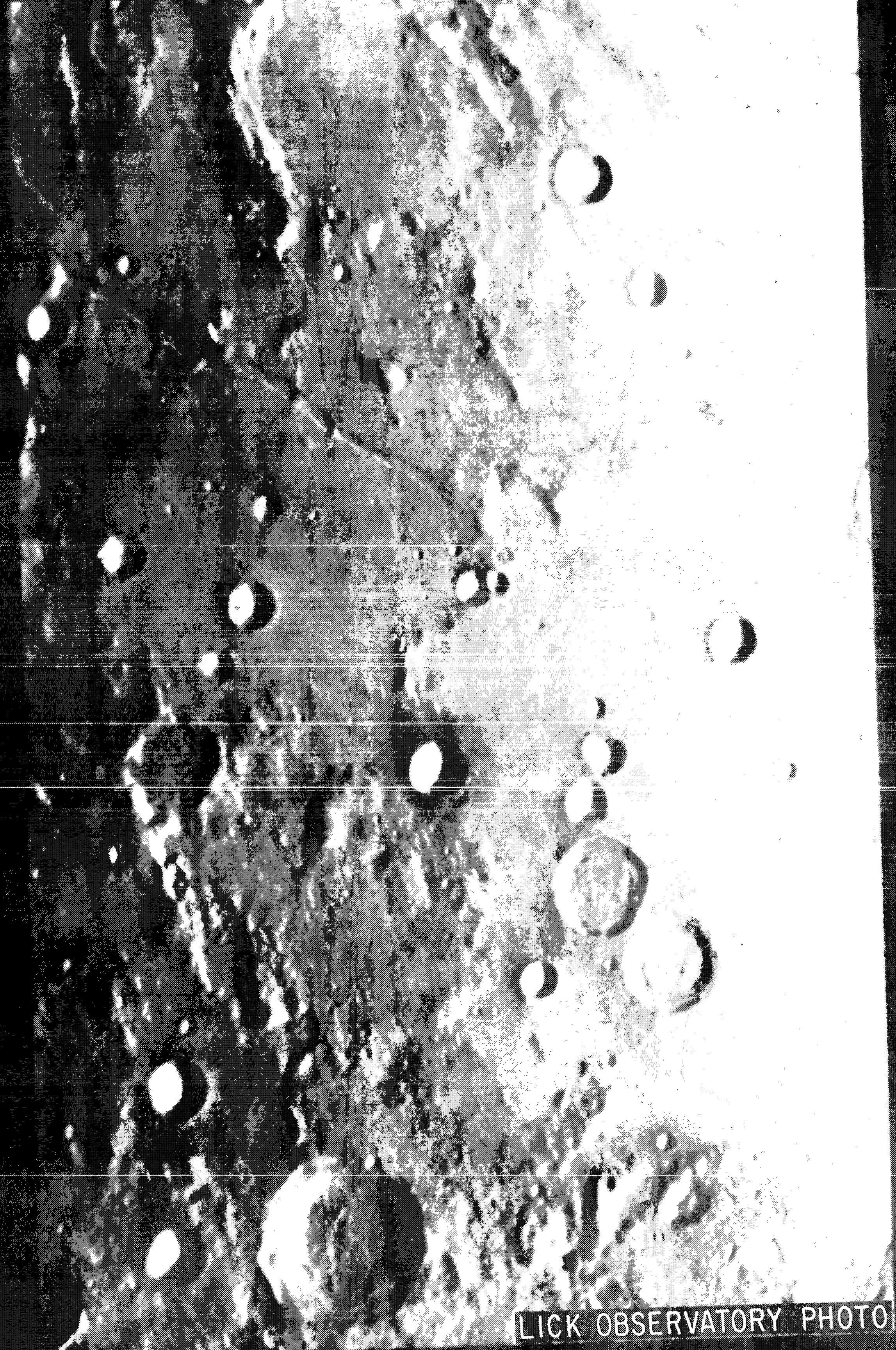


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Fig. 2

Fig. 3

Fig. 4

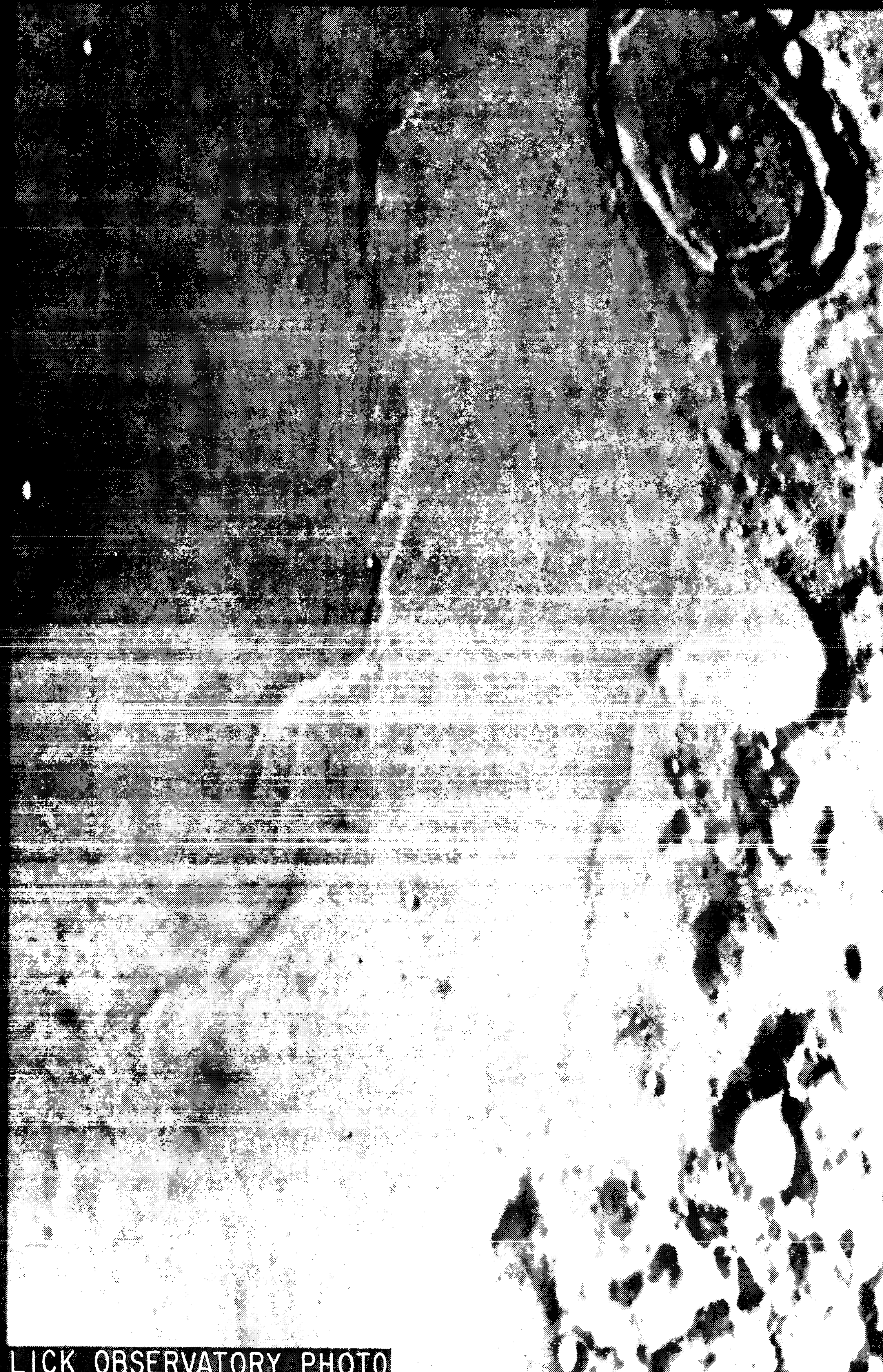

Fig. 5

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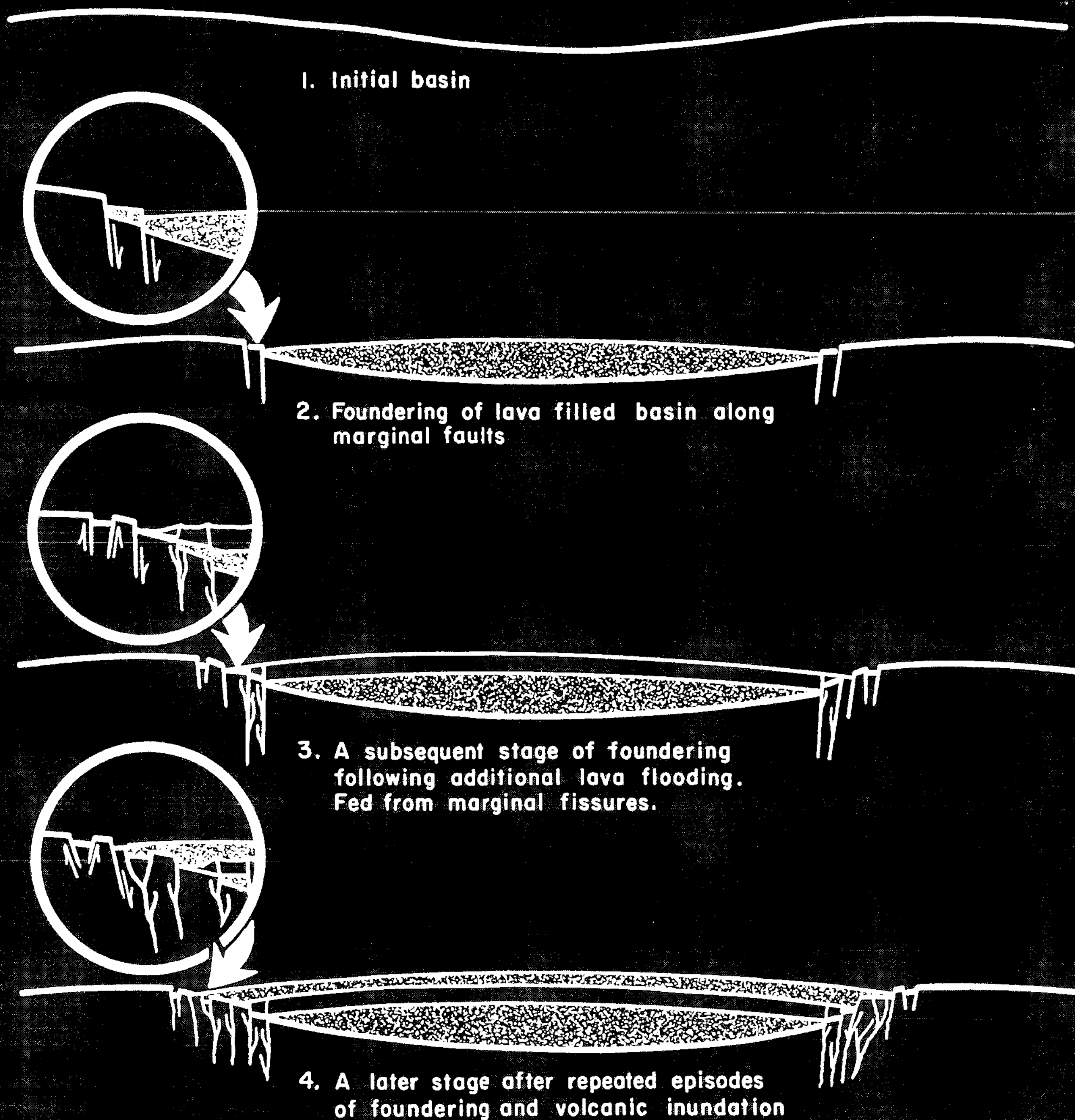

Fig. 6

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